Angular Distribution of Zeeman Photon Pairs in a Highly Scattering Medium

Hsiu-Fong Chang[1,2], Yi-Shin Chan[3], Jenq-Nan Yih[1], Hon-Fai Yau[1], Jen-Chuen Hsieh[4],
Chien Chou*[5]
[1]Institute of Optical Sciences, National Central University
[2]Kuang Wu Institute of Technology
[3]Faculty of Medicine, School of Medicine, National Yang-Ming University
[4]Brain Research Unit, Taipei Veterans General Hospital
[5]Institute of Radiological Sciences and the Department of Medical Radiation
Technology, National Yang-Ming University

ABSTRACT

The angular distribution of the photon pairs of a Zeeman laser scanning confocal microscope (ZLSCM) is measured in turbid media. By scanning the pinhole at different locations on a focal plane, the angular distribution of the snake photon pairs that is contributed by the object plane in the scattering medium is measured. The narrower width of the angular distribution of the snake photon pairs implies the better performance of the depth resolution of ZLSCM in turbid media. In this study, the dependence between depth resolutions of ZLSCM with respect to different vol. % concentrations of the scattering medium is observed. In addition, the correlation between angular distribution and depth resolution in different concentrations is also demonstrated and discussed.

Keywords: confocal microscopy, turbid media, polarization, tomography

1. INTRODUCTION

An angular distribution of photon pairs, which propagate in the scattering medium, is measured in ZLSCM. A photon pair consists of two correlated photons. Both photons are linear polarized and orthogonal with each other.

---

[1]Institute of Optical Sciences, National Central University, Chung-Li, Taiwan 320
[2]Kuang Wu Institute of Technology, Taiwan, Pei-Tou,Taipei,Taiwan 112
[3]Faculty of Medicine, School of Medicine, National Yang-Ming University, Pei-Tou, Taipei, Taiwan 112
[4]Brain Research Unit, Taipei Veterans General Hospital,Pei-Tou,Taipei,Taiwan 112
[5]Institute of Radiological Sciences and the Department of Medical Radiation Technology, National Yang-Ming University, Pei-Tou, Taipei, Taiwan 112
*cchou@ym.edu.tw; phone 886-2-28267061; fax 886-2-28251310

Polarization Measurement, Analysis, and Applications V, Dennis H. Goldstein, David B. Chenault, Editors, Proceedings of SPIE Vol. 4819 (2002) © 2002 SPIE · 0277-786X/02/$15.00

Their temporal frequencies are different. Thus, the spatial coherence and the degree of polarization of photon pair propagating in the scattering medium determine the ability of generating the heterodyned signal when the scattered photon pairs pass through a Glan-Thompson analyzer in ZLSCM. Therefore, a pinhole and a band pass filter can be used to select the snake photon pairs reflected from the object plane in the scattering medium and then to reject multiple scattering photons simultaneously. In the confocal microscopic configuration of this experiment, a pinhole is displaced laterally from the focal point of microscope objective. Different scattering angles of snake photon pairs are focused onto the pinhole at different locations. The snake photon pairs were then detected, heterodyned and filtered by a photomultiplier and a band pass filter. Meanwhile, the pinhole as well as the band pass filter suppress the multiple scattering photons in the medium simultaneously. It is because the angular distribution of the photon pairs determines the performance of the depth resolution of ZLSCM. The narrower width of the angular distribution of the snake photon pairs implies better performance of the depth resolution of the system in turbid media. In this study, the performance between depth resolutions with respect to different vol. % concentrations of the scattering medium is shown. In addition, the correlation between the angular distribution and the depth resolution in different concentrations is demonstrated and discussed

2. PRINCIPLE

A Zeeman laser that includes two orthogonal linear polarized waves, P waves and S waves with different frequencies, as a photon pair, propagates in the scattering medium. The reflected weak-scattering photon pairs and the multiple-scattering photons pass though a Glan-Thompson analyzer that is located between two identical objectives. If the temporal frequencies of the P and S waves of the Zeeman laser are ω_p and ω_s, respectively, and the central frequency of the band pass filter is set at $\Delta\omega = \omega_p - \omega_s$, the reflected and filtered heterodyne signal can be expressed as

$$I_{out}(\Delta\omega t) = R_f \sqrt{I_p\, I_s}\, \sin 2\theta_s \cos(\Delta\omega t) \tag{1}$$

where θ_s is the azimuth angle of the analyzer (see Fig. 1); I_p and I_S are the intensities of the scattered P wave and S wave, respectively; R_f is the reflectance of the object. The scattering effect can be greatly reduced when the scattered P and S waves are heterodyned with each other[1, 2] due to the dependence of the reduced scattering coefficients μ_s' on the refractive index of the scattering medium. In addition, the scattering properties of both P and S waves are similar in the scattering medium. Therefore, the scattering coefficients of P wave and S wave subtract each other when the analyzer optically heterodynes them[3].

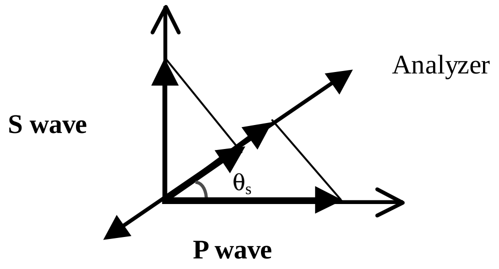

Fig. 1 P and S waves transmitting through the analyzer

3. EXPERIMENTAL SETUP AND RESULTS

Figure 2 shows the optical configuration of the experimental setup where a ZLSCM is constructed[2]. The reflected photon pairs from object plane which is located on the focal plane of the first objective L_1 transmit the scattering medium that induces a wavefront distortion as shown in Fig. 3. Thus, the distorted wavefront can be decomposed into plane waves in different propagation vectors. A second objective L_2 which is identical to L_1 focuses the plane waves onto focal plane of L_2 at different locations. The off-focus scattered photon pairs are then screened by a pinhole due to the spatial gating capability of the system. In the mean time, the analyzer which plays the function of polarization gating is able to select partial polarized and partial correlated photon pairs that contributes the heterodyne signal in this setup.

In the measurement, the pinhole was scanned laterally on the focal plane of L_2 in order to measure the angular distribution of partial polarized scattered photon pairs from object plane in the turbid medium. During the measurement, the angular distribution of on-focus snake photon pairs becomes narrower in a higher concentration of the scattering medium in which 0.992μm polystyrene microsphere suspension was diluted in water[4,5] (see Fig. 4). The correlation between the depth resolution of ZLSCM and the angular distribution of photon pairs is shown in Fig. 5. The higher concentration of the medium, the narrower the angular distribution and the better depth resolution will be. In addition, according to Mie theory[6, 7], the depolarization of linear polarized photon pairs versus particle sizes of the scatters implies the correlation between the smaller particle size of the scatters and the narrower angular distribution. Furthermore, the depth resolution of ZLSCM relates to the particle size of the scatters is shown in Fig. 7. The volume concentration of polystyrene microspheres suspension diluted in water is fixed at 1.5%. The particle sizes are 0.992μm, 4.562μm or 5.632μm, respectively. These results show the smaller the size of the scatter, the narrower the angular distribution. And later, better depth resolution of ZLSCM in the scattering medium follows.

A sample of a letter “M” was imaged tomographically in the scattering medium. The sample was produced based on laser ablation technique by using an excimer laser. A polycarbonate substrate was used so that a letter “M” was ablated from the surface of the substrate. It was then coated with a gold film on the surface in order to improve the uniformity and the reflectivity of the sample. The surface profile of the sample was scanned by a surface profiler (New View 5000, ZYGO Inc.). The depth of the letter “M” is 24μm below the top surface of the sample. Figure 8 shows the tomographic image of letter “M” immersed in the scattering medium that is a polystyrene microphere suspension diluted in water of 2% vol. concentration. The size of polystyrene microphere is .0992μm in this solution. The immersion depth of the tested sample is 1000μm in the scattering medium. This results the reduced optical thickness $(\tau'=\mu_s'\times 2L)=60$ in the experiment. It is apparent that in Fig. 8, the tomographical image is achievable in an arrangement where the top surface of the sample is focused during the measurement. Thus, the intensity of the image of letter “M” is relatively weaker than the image intensity of on focus top surface of the sample due to the finite width (FWHM=50μm) of depth resolution of ZLSCM. The non-uniform intensity of the image “M” is caused by the reasons of non-uniformity of the reflectivity and the surface roughness of letter “M”. They are induced during the laser ablation process. From Fig. 8, the experimental result confirms the tomographic capability of ZLSCM. In comparison with the depth resolution of several hundred micrometers of conventional confocal microscope in a turbid medium[5], ZLSCM improves the depth resolution in turbid medium.

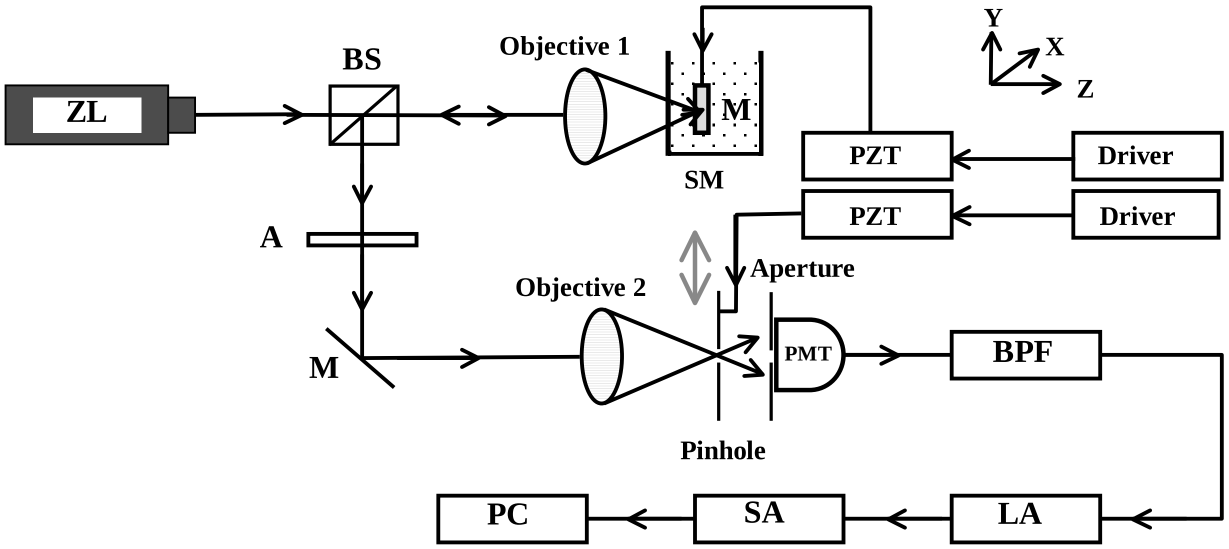

Fig. 2 ZL, Zeeman laser; BS, beam splitter; M, mirror; SM, scattering medium; PZT, piezoelectric transducer; A, analyzer; PMT, photomultiplier tube; BPF, band pass filter; LA, linear amplifier; SA, spectrum analyzer; PC, personal computer.; 20X objective(12mm working distance, NA=0.4).

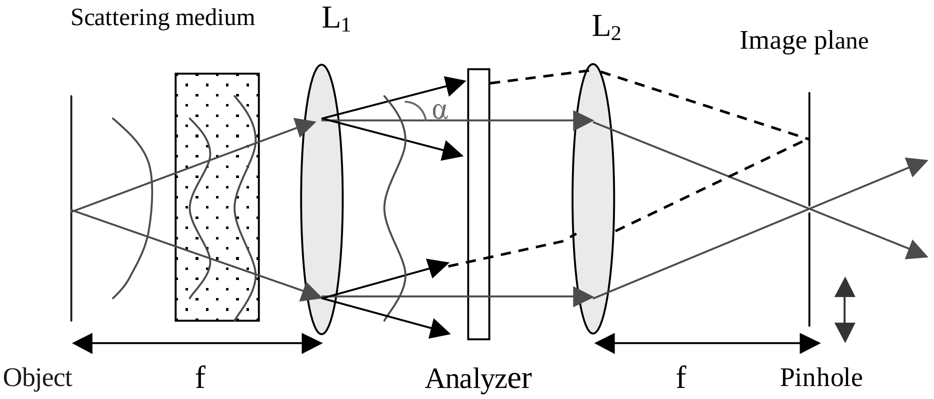

Fig. 3 The angular distribution of photon pairs in the scattering medium

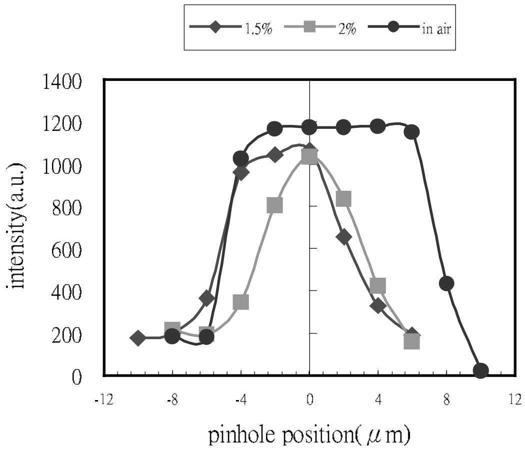

Fig. 4 The angular distribution of scattered photon pairs versus volume concentration of 0.992μm polystyrene microsphere suspension diluted in water.

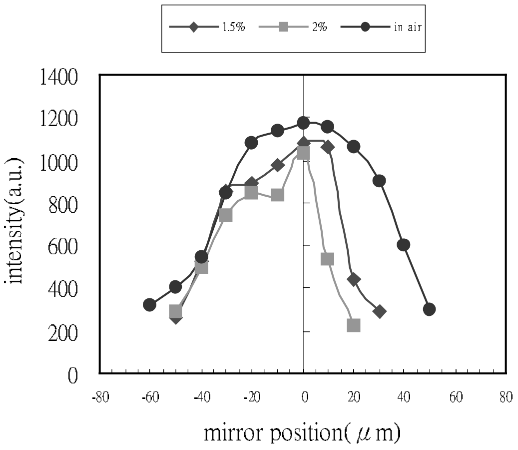

Fig. 5 The depth resolution of the scattered photon pairs versus volume concentration of 0.992μm polystyrene microsphere suspension diluted in water .

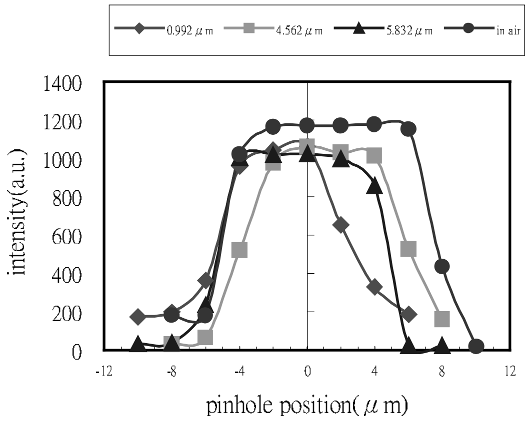

Fig. 6 The angular distribution of scattered photon pairs versus scattered sizes of polystyrene microsphere suspension at 1.5% vol. concentration.

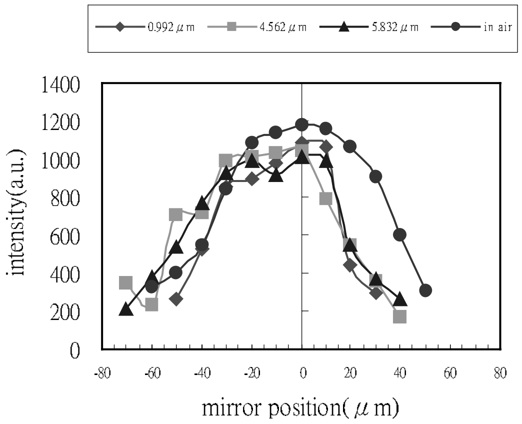

Fig. 7 The depth resolution of scattered photon pairs versus different scattered sizes of polystyrene microsphere suspension at 1.5% vol. concentration.

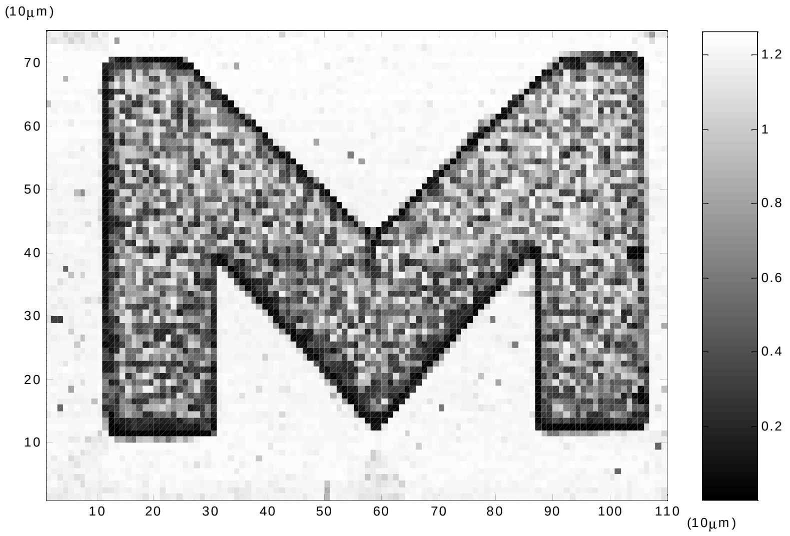

Fig. 8 A tomographic image of letter “M” immersed in the scattering medium of polystyrene microsphere (0.992μm) suspension diluted in water of 2% vol. concentration.

4. CONCLUSION

In the research, the angular distribution of the scattered photon pairs from Zeeman laser in the scattering medium was measured. The depth resolution of ZLSCM relates to the volume concentration as well as the particle sizes of the scatters are studied. We found that the higher concentration of the scattering medium and the smaller size of the scatters present a better depth resolution of ZLSCM. The results confirm that the Zeeman photon pairs propagating in the scattering medium perform better abilities of selecting the snake photon pairs and suppressing the multiple scattering photon that are contributed by the polarization gating and the coherence gating. In conclusion, the scattering medium having smaller size of scatters with higher concentration results in narrower angular distribution of the scattered photon pairs in the turbid medium. Then a better performance on depth resolution of ZLSCM in the scattering medium is achievable.

ACKNOWLEDGMENTS

The study was supported by the Excellent Project of the Ministry of Education (grant NSC/MOE 89-B-FA-22-1-4-01) of the Republic of China. Ms. J. C. Jan’s assistance in preparing the manuscript is appreciated.

REFERENCES

1. C. Chou, L. C. Peng, Y. H. Chou, Y. H. Tang, C. Y. Han, and C. W. Lyu, “Polized optical coherence imaging in turbid media by use of a Zeeman laser,” Opt. Lett. **25**, pp. 1517-1519, 2000.
2. L. C. Peng, C. Chou, C. W. Lyu, and J. C. Hsieh, “Zeeman laser-scanning confocal microscopy in turbid media,” Opt. Lett. **26**, pp. 349-351, 2001.
3. J. B. Fishkin, P. T. C. So, A. E. Cerussi, S. Fantini, M. A. Franceschini, and E. Gratton, “Frequency-domain method for measuring spectral properties in multiple-scattering media: methemoglobin absorption spectrum in a tissuelike phantom,” Appl. Opp. **34**, pp. 1143-1155, 1995.
4. J. M. Schmitt, A. Knittel, and M. Yadlowsky, “Confcal microscopy in turbid media,” J. Opt. Soc. Am. A **11**, pp. 2226-2235, 1994.
5. C. Yang, K. An, L. T. Perelman, R. R. Dasari, and M. S. Feld, “Spatial coherence of forward-scattered light in a turbid medium,” J. Opt. Soc. Am. A **16**, pp. 866-871, 1999.
6. I. A. Vifkin, “Polarization studies in multiple scattering chiral,” Opt. Eng. **39**, pp. 353-362, 2000.
7. S.P. Morgan, M.P. Khong, and M.G. Somekh, “Effects of polarization state and scatter concentration on optical imaging through scattering media,” Appl. Opt. **36,** pp. 15601565, 1997.